CHAPTER I

MODERN BALLISTIC RANGES AND THEIR USES

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Laboratory facilities such as ballistic ranges and wind tunnels invariably are conceived and developed to meet particular existing or anticipated needs. The need may be purely intellectual as in the case of electron and ion accelerators for nuclear research, or it may be very practical as in most engineering facilities - like the ballistic range - where problems of immediate concern to engineering advancement can be studied and solved. Occasionally, the ballistic range serves to answer purely intellectual questions as well.

Until the early 1940's, the emphasis in ballistic-range studies lay almost exclusively in perfection of various spin-stabilized shell for weapons. Gyroscopic stabilization of these projectiles, which were usually aerodynamically unstable in nose-forward flight, resulted in intricate yawing motions composed of precessions and nutations. Analysis of the real motions of bullets to determine the complete aerodynamic force and moment systems was a challenging task which should not yet be considered complete in all details. Analysis of these motions also yielded the aerodynamic drag force, which exerts a first-order influence on range, and the lift force, which influences dispersion.

In the past quarter century, however, the use of the ballistic range has broadened, until the study of the original ballistic problems has perhaps assumed secondary importance. Development of new uses has been stimulated by problems of vehicles proposed to fly at very high speeds in the atmosphere for military, commercial, and scientific purposes. These efforts include the development of transonic, supersonic, and hypersonic airplanes and missiles. A particular field of intense interest has been atmosphere entry of long-range missiles and space vehicles after flight outside the atmosphere. Emphasis has therefore shifted toward research in such disciplines as hypersonic aerodynamics, aerodynamic heating, and materials behavior under severe thermal and mechanical stress.

To say that these new missions stimulated development of the new techniques and uses of the range does not adequately imply the intimate connection between need and use. The ballistic range, in concert with other devices such as shock tubes, arc-jets, and electronic computers, made possible the swift advance of flight technology; for without these tools, prohibitively expensive and time-consuming full-scale flight-testing would have been required. Alternatively, reliance on inadequate simulation provided by more conventional facilities would have led to sometimes inaccurate and incomplete descriptions of the problems, and therefore inappropriate solutions. The advancements in capability which have kept the modern ballistic range equal to its task may be grouped in three classes: higher gun performance, new instrumentation, and greater range of flight-chamber environment.

The remainder of this chapter is intended as a look at the features of modern ballistic ranges and the kinds of research done in them. As such, it serves as a short preview of the topics covered in the remaining chapters and relates the chapters to one another.

1.1 GUNS

Until the 1950's the highest performance guns used the gases generated by gun powder to fire projectiles for range tests. While the powder gas gun still retains the advantage of operational simplicity and continues to be useful as a research tool at low and intermediate speeds, it does not provide the high speeds demanded by many studies of current interest. A considerable literature exists dealing with the construction and operation of the powder gun. Therefore, the discussion of guns in this book is limited to light-gas guns, which use highly compressed hydrogen or helium to propel research models in the laboratory.

By substituting hot hydrogen or helium for the gun-powder gases (low versus high molecular weight and high versus low sound speed), muzzle velocities have risen from around 2 to about 6 km/sec for fairly slender (i.e., delicate) metal models. For bluff (and potentially stronger) models the speed increase has been roughly from 3 to 9 km/sec and a few tests have been accomplished at 11 km/sec.

The modern gun operates in much the same way as does a child's pop-gun. The propellant gas is rapidly compressed by means of a free piston in a long cylinder (the pump tube). When the propellant pressure exceeds a preselected level, the gas is admitted to the breech of the launch tube, where it forces the model to accelerate to high speed. During the model's traverse of the launch tube the piston continues to compress the reservoir of hydrogen by virtue of its momentum. This results in a programmed variation of hydrogen pressure in the reservoir (at the launch-tube breech), which significantly reduces the peak acceleration and increases the ultimate muzzle velocity attainable. The very bulk and complexity of this system probably rule out military or sporting service, and the light-gas gun will probably remain a laboratory tool.

1.2 MODELS

The design and construction of the model and its carrier in the gun barrel, (called the sabot), are at the very heart of the successful test. The model must have the external form of the object to be simulated, and it must withstand the enormous launch acceleration, on the order of 10^6g, without damage. Its surface qualities and center of mass must frequently simulate those of the vehicle as well. In the case of terminal ballistics studies it is usually made of the same material as the actual projectile or meteoroid. The chemistry of the model surface may be prescribed by the need to provide the correct constituents in the wake. Furthermore, it is clear that the model must survive the rigors of flight through the test section. One severe test is withstanding convective heating rates that are 10 to 100 times those in full-scale flight.

A combination of rational design and empiricism has been developed to meet these seemingly impossible demands, and the general approach is outlined in Chapter 3 along with copious examples of successful designs.

1.3. PHOTOGRAPHIC STATIONS AND FLOW PHOTOGRAPHY

To record the position and attitude history of the model flight, most modern ballistic ranges use photographic stations. These respond automatically to the approach of the model, and fire either a very short-duration spark or a spark and an electro-optical shutter (Kerr cell) to expose the film, most often with a silhouette image of the model, as described in Chapter 6. Lasers and X-ray tubes are being used as well. Position and attitude references within the field of view are also recorded on the film to permit accurate measurements of three linear coordinates and at least two angular coordinates in each pair of orthogonal photographs. The time intervals between spark or shutter firings are measured to fractional-microsecond accuracy, in modern practice usually by electronic counter-chronographs.

The usual optical arrangement to make a shadow picture, namely, a spark and film on opposite sides of the flightpath, produces an important bonus - it makes key features of the flow field visible in the photograph. This basic shadowgraph, its variations, and other systems for flow visualization (Schlieren, interferometer) are described in Chapter 8. Such photographs can reveal the nature of the flow in great detail and have been the basis for understanding of high-velocity-flow configurations and phenomena. In fact, many range studies have consisted almost solely of careful scrutiny of many shadowgrams in order to arrive at empirical descriptions of the flow. An excellent example is in the study of laminar-turbulent transition of the boundary layer, and another is the study of conditions for attached or separated flow. The photographs also sometimes permit the tracing of Mach waves and streamlines. These and other uses of flow visualization are developed in Chapter 8, along with the theory of flow visualization, which makes the interpretation of flow photographs both rational and potentially quantitative.

Not to be overlooked either is the unequivocal recording of the condition of the model in flight. Simply because a model is undamaged when first photographed is no reason to expect it to maintain this perfect condition. The intense convective heating, resulting from high-speed flight; will in many cases raise metal surfaces to the melting point or plastic surfaces to the boiling point. Shadowgraphs frequently record these features and so add to the observable phenomena available for study (e.g., quantitative use has been made of the determination of the onset of melting in measurement of heat-transfer rates, as described in Chapter 12).

1.4 MOTION ANALYSIS

The combination of shadowgraph photography and accurate reference systems means that the flight of any object through the range can, at least in principle, be recorded so accurately and completely as to enable determination of the complete aerodynamic force and moment system. The analysis of motion histories has evolved from early empirical, subjective observations of what constituted satisfactory flight behavior to meticulous curve-fitting programs which "find" that set of coefficients for the linearized equations of motion of lightly damped, slightly asymmetric, rolling bodies which best matches the observed data (Chapter 7). The evolution in data analysis since 1940 has consisted mainly of a gradual elimination of restrictions inherent in the equations. This progress has been permitted in no small part by the development of high-speed computers.

Until quite recently, analysis of nonlinear systems has been accomplished only by patching together "equivalent linear systems." It presently appears practical to relax the restrictions in data analysis still further to permit fitting of numerical solutions of highly nonlinear equations of motion directly to the trajectory data. Early efforts in this major development are outlined in Chapter 7, but the problem has by no means been completed.

Prediction of large-scale flight characteristics on the basis of small-scale flight tests is generally quite successful when the test data are taken at comparable values of Reynolds number, Mach number, and other simulation parameters, and when all degrees of freedom essential to the flight case are recognized and included. Such additional factors as surface roughness, surface temperature and ablation, and Knudsen number may enter as well. No laboratory aerodynamic testing device excels the ballistic range in permitting simultaneous duplication of Reynolds number, Mach number, and enthalpy. As pointed out later, simulation of nonequilibrium real-gas flows may deteriorate as a consequence of small model scale. These latter effects are usually of importance only in cases where the gas state and kinetics are the object of study. Comparison of ballistic-range tests of the Apollo command module with results from wind tunnels and from actual entries shows little evidence that aerodynamic behavior is affected by these chemical and kinetic differences in the flow fields.

Chapter 7 shows a detailed comparison of lift, drag, and stability data, using the AGARD model (HB-2), obtained in ranges and wind tunnels. Where disagreements are found, they are easily explained. Thus the comparisons both with other laboratory techniques and with large-scale flight vehicles validate the force measurements made in the range (if indeed they should be questioned).

1.5 MODIFICATIONS OF THE TEST ENVIRONMENT

The essential ingredients of the modern ballistic range are: (1) a light-gas gun; (2) models to be tested; (3) photographic stations to record the flights; (4) a chronograph to provide accurate records of operation of the photographic stations; and (5) a butt or target to stop the projectile. Beyond this, the special purposes of the range begin to dictate the detailed design of the basic parts and selection of additional features and equipment.

1.5.1. Variable Pressure, Temperature, and Composition

An important variation of the basic ballistic range is its enclosure in a steel tube to permit variations in the composition, pressure, and termperature of the test gas, first practiced at Ballistic Research Laboratories, Aberdeen, Maryland. The range of pressures thus achievable extends from about 10^{-6} atmosphere to several atmospheres, while the minimum temperature is limited only by liquefaction of the gas used. Pressure control yields direct control over Reynolds number; temperature control, which varies the speed of sound, gives independent control of Mach number. At low temperature, high Mach numbers are easily achieved. Substitution of exotic gases for air permits simulation of flight at other planets or the fundamental study of gas-property effects on gas dynamics.

Pressure control is invaluable in terminal-ballistic work as well. With the range tank evacuated, the influence of aerodynamic shock waves on the target is eliminated and the loss in projectile speed between gun muzzle and target is minimized.

The tank, pumps, and piping represent only part of the cost of this valuable improvement of the basic ballistic range. The entire photographic and reference system must be adapted to the pressure tank, while the gun muzzle must be coupled into it as well. Further, special tanks, structures, and valves are frequently required to absorb and contain the gun-muzzle blast and stop the sabot parts before they enter the test area. Some of these complications are treated in Chapter 6.

1.5.2 Countercurrent Airstream

A modification to the test environment which increases both the speed and Mach number capabilities of the ballistic range is to incorporate a supersonic airstream blowing towards the gun (Chapter 5). This was first applied at Ames Research Center. The counterflow was initially an airstream blowing at a Mach number of two from a large reservoir and discharging to atmosphere. The free-stream temperature was about 175°K so that the depressed speed of sound - 250 meters per second - and the velocity added directly by the airflow made hypersonic testing feasible with ordinary guns using smokeless powder. For example, a muzzle velocity of 2 km/sec yielded a Mach number of 10.

Another interesting counterflow facility, called the Atmospheric-Entry Simulator, used the density distribution within a long, continuously expanding nozzle to create a laboratory simulation of the altitude variation of density in the Earth's atmosphere. When high-speed models of entry bodies are fired through this simulated atmosphere, the heating history of entry bodies is remarkably well simulated, except for effects of radiation by the model surface and by the heated gases in the model flow field. This facility was built and used for several years at Ames Research Center.

As in the case of the pressure-vacuum tanks, the counterflow feature requires that other aspects of the design be compromised. Most important, the test-range length is limited to the length of test section in which a high-quality supersonic airflow can be maintained. Viscous effects produce a turbulent boundary-layer flow on the walls which ultimately fills the test section. The deceleration of the stream produced by this boundary layer effectively reduces the cross-sectional area of the tube; therefore the test section must be constructed with a slowly increasing cross section to compensate.

To match the ever-increasing speeds of interest, countercurrent streams of higher Mach number and higher enthalpy are called for. Preheating the working fluid to permit such performance with a simple blowdown wind tunnel becomes increasingly difficult and expensive. An alternative approach is to use a large shock-tube wind tunnel. In this device the air can be heated to a stagnation temperature of several thousand degrees Kelvin and expanded to much higher speeds and Mach numbers than possible in the earlier unheated blowdown flows. The flow duration is of course orders of magnitude shorter than that possible in the simple blowdown tunnel but is nevertheless quite compatible with the short observation times needed (milliseconds) with fast moving projectiles in available test section lengths. This type of counterflow was first introduced at Ames, and the largest such facility has a test section 23 meters in length by 1.2 meters in diameter. Test speeds up to 13 km/sec have been obtained, and 16 km/sec appears possible.

1.6 SPECIAL MEASUREMENT TECHNIQUES

As the speeds attainable have increased along with the controllability of the test environment, additional kinds of experiments have become possible; these new studies usually have required introduction of new types of instrument into the range. A few examples of these new experiments and their necessary instruments will illustrate the expanding research possibilities presented.

1.6.1 Thermal Radiation from Gases

The air near the path of a blunt, high-speed model is intensely heated by the passage of the bow wave. Temperatures above 10,000^{o}K can be attained; and even at speeds around 4 km/sec, where the maximum temperatures are only about 4000^{o}K, the gas becomes luminous. The model itself may become luminous by virtue of intense convective heating. Other phenomena which emit measurable radiation occur in the wakes and in the impact processes at the target.

Introduction of radiometers (Chapter9) to measure these thermal emissions has become a principal field of investigation in ballistic ranges. It has permitted verification of theoretical calculations of the thermodynamic and chemical properties of the immediate flow fields of the bodies and their wakes. Several contributions to the literature of molecular physics have come from such studies. In particular, the thin layer of hot gas which forms over the face of a nearly flat-nosed body is a well-characterized sample of hot uncontaminated gas (outside the region into which products of ablation diffuse). The emission from such shock layers has been successfully used in establishing some of the fundamental radiative properties of nitrogen, oxygen, and carbon dioxide, and mixtures thereof.

Simulation of radiative effects in full-scale flow fields is reasonably good except that nonadiabatic effects, important at very high speeds for large blunt vehicles, do not affect the flow importantly at model scale. Similarly the small scale of the tests degrades the simulation of chemical-kinetics effects. For the most part, however, the emphasis in radiation measurements is properly placed on testing theoretical estimates of radiation rather than on simulation of full-scale events.

An exception to this is in studying the spatial distribution of radiation within the shock layer of bluff bodies, particularly at large angles of attack. The difficulty of calculating such flows makes even the somewhat questionable simulation in the range quite desirable.

Another example of radiometry in the range is measurement of the thermal emission resulting from impact of projectiles into targets. The emission has been related to, among other more obvious variables, the ambient-gas composition and pressure.

Since the duration of events in the ballistic range is extremely short (the entire flight usually requires only a few milliseconds), very high-frequency-response radiometers must frequently be used. The design and absolute spectral calibration of these radiometers is detailed in Chapter 9.

1.6.2 Microwave and Other Techniques for Measuring the Wake

The heated flows produced by passage of the models are characterized by increased electron density as well as by radiative emission and absorption. One of the more powerful techniques for studying the electrical properties of plasmas is microwave interferometry (Chapter 10). The opportunity to study simulated wakes of entry bodies in the laboratory has led many investigators to install microwave equipment in enlarged variable-pressure ranges to measure electron-density, turbulence spectra, and flow-velocity variations along wakes as influenced by the usual aerodynamic parameters and by the material of which the model surface is made.

If short-wavelength equipment is used, careful design of lens systems can yield sufficient spatial resolution to determine the radial distribution of free electrons in the wake with modest accuracy.

The linear electron density of the wake, that is, the number of free electrons per unit length, is most easily determined by measurement of the power dissipation in a resonant cavity through which the model has been fired.

The study of flow fields and wakes, using microwave techniques, shares the imperfect simulation which limits the study of thermal emission. If the nondimensional fluid mechanical parameters such as Mach and Reynolds numbers are simulated, the absolute air density must be greater than in full-scale flight by the scale factor. Thus the equilibrium chemical and thermodynamic properties (as well as three-body-collision chemical reactions) are not faithfully scaled. The tests are best viewed as elaborate exercises in verification of complete theoretical models, which can presumably apply to the case of full-scale vehicles.

Radar can be utilized as well. Several ranges have been equipped to allow a CW microwave radar beam to "look" uprange from a reflector near the butt. The signal return can yield measurements of the model velocity, deceleration, and radar cross section (the apparent size of the model and its ionized flow field). By mounting the microwave antenna on the gun muzzle to establish a standing-wave system in the barrel, the time-history of projectile travel in the gun barrel itself can be measured. The resulting measurements of acceleration are invaluable to the ballistician, because he can deduce the actual propellant pressure history, as discussed in both Chapters 2 and 10.

A variety of instruments, in addition to the microwave interferometer, are available to measure the plasma and gas-dynamic properties of model wakes in the ballistic range. A whole family of these instruments is being established to make local "point" measurements in wakes (Chapter 11). Most of these devices are taken from earlier technology and are simply adapted to the ballistic-range environment (e.g., Langmuir Probes, hot-wire anemometers, microphones). One technique merits particular mention because of its utility in measuring flow speed in turbulent gases. This is the marking of a filament of the moving gas by discharging a high-voltage spark through it; then after suitable time delays, additional discharges are produced along the same, but progressively more distorted, filament. Stereoscopic photographs of the entire sequence record the changes in the filament shape with time, and thus indicate the velocity distribution existing at that station of the wake.

1.6.3 Heat-Transfer Measurements and Telemetry

Although high levels of convective aerodynamic heating occur in ballistic-range tests - larger by the scale factor than on large scale vehicles at the same velocity and Reynolds number - the measurement of heat transfer is not readily accomplished. Several different approaches have, however, been successfully developed and applied (Chapter 12). One conceptually simple method is to decelerate the model aerodynamically within the range to a low speed (by selection of the model mass and scale, and the ambient density and range length), and to recover it at the end of flight in a sensitive calorimeter which records the total heat content. Differentiation of the data from a number of firings at different muzzle velocities permits the determination of heating rate as a function of velocity. Another method, involving shadowgraph detection of the onset of ablation of low-melting alloy models (aluminum has been used), has already been alluded to. The companion phenomenon to heat transfer, boundary-layer skin friction, has been successfully measured by testing slender models whose drag is predominantly skin friction, and correcting measured total drag for the wave- and base-drag contributions.

In one application the drag of long and short thin tubular models with sharp leading edges was measured. The differences in drag and wetted area were used to derive the incremental skin-friction drag.

A potential method of measuring heat transfer, which has challenged many investigators over the years, is the use of telemetry to transmit from the free-flight model a signal proportional to temperature rise of a sensor placed at a selected location. Telemetry, of course, would have applications to many other measurements, including pressures and accelerations. The meager success of many vigorous efforts to develop transducers and miniature transmitters does injustice to the skill and determination of the engineers involved. The critical problem which has blocked complete success is that of producing frequency-modulation transmitters and pressure gages - not to mention batteries - capable of withstanding peak accelerations approaching 10^6g (required in the gun to achieve interesting speeds). The prospects of achieving useful results are further dimmed by the possibility of interference with and severe attenuation of the radiated signal by the thin plasma sheath surrounding the test body at the high flight velocities of interest in heat-transfer work.

One rudimentary telemetry system has successfully transmitted temperature data from tiny models fired at speeds up to 6 km/sec. No active electronic parts were included in the model; rather, a thermocouple at the model surface was connected directly to a small coil. The small current through the coil (resulting from rising surface temperature) produced a magnetic field, which was measured using multiple-turn coil antennae through which the model flew at high speed. Details are given in Chapter 12.

1.7 TYPICAL RANGES

During the last two decades the ballistic range has expanded its place in the family of engineering and scientific laboratory tools. Its qualities have complemented those of wind tunnels, arc-jets, and shock tubes, both by improving laboratory simulation of large-scale flight at very high speeds and by providing freedom from some of the imperfections inherent in other test devices.

In order to indicate the breadth of acceptance and application of the hypervelocity ballistic facility, a brief listing has been prepared of laboratories in which light-gas guns are used. The listing is limited to Western Europe and North America and is far from complete.

The elaborate array of ballistic-range facilities suggested by these entries attest to their wide use in governmental and industrial laboratories. The lengths of the ranges extend from a few meters to several hundred meters; the sizes of light-gas guns used range from less than 10 mm to over 100 mm in caliber and permit muzzle velocities over 10 km/sec. The purposes to which these ranges have been applied are diverse, and it is expected that they will become more so with the passage of time.

TYPICAL MODERN BALLISTIC RANGES

Facility	Application	Dimensions: Length m	Dimensions: Diameter m	Dimensions: Gun size mm	Photographic stations (Number of orthogonal units): Shadowgraph	Photographic stations: Schlieren	Photographic stations: X-ray	Microwave	Radiometer	Pressure range atm	Comments
NOL 1000ft Hyperballistics Range[a]	Aerodynamic stability Wake study	305	3	50-100	37	-	5	3	12	$1\text{-}4\times10^{-4}$	270 meters usable for stability.
NOL Pressurized Range	Aerodynamic stability Wake study	87	1	13-400	32	2	4	-	-	$6\text{-}2\times10^{-4}$	Controlled temperature section; 7-meter section for continuous wake study.
CARDE Range No. 5[b]	Aerodynamic stability	120	3	-	Varies	-	11	-	-	-	Nonorthogonal X-ray stations for model position.
RARDE Pressure Range[c]	Aerodynamic stability	22	0.6	6	16	-	-	-	-	$10\text{-}10^{-5}$	
LRBA Tunnel Hyperbalistique[d]	Aerodynamic stability	75	1.2	-	12	-	-	-	-	$7\text{-}4\times10^{-5}$	
VKF 1000ft Hypervelocity Range[e]	Aerodynamic stability	305	3	63	43	-	-	-	-	$1\text{-}10^{-4}$	270 meters usable for stability.
NASA-Ames Aerodynamic Facility[f]	Aerodynamic stability	25	1	7-38	16	-	-	-	-	$1\text{-}10^{-3}$	Part of M = 7, shock-driven countercurrent wind tunnel.
MIT Range A[g]	Wake study Aerophysics	30	0.3-1.5	20	5	1	-	Varies	Varies	$1\text{-}10^{-8}$	Stainless-steel construction; can be kept clean.
ISL Aeroballistic[h]	Wake study Aerophysics	8.5	2	20	13	-	-	Varies	-	-	
NOL Aerophysics Range	Aerophysics	100	12	9	Varies	-	-	-	Varies	$1\text{-}1\times10^{-4}$	Mach-Zehnder interferometer. 4 rotating-mirror cameras.
GM-AC-DRL Aerophysics Range B[i]	Wake Study Aerophysics	55	0.6-2.5	20	5	3	-	Varies	4	-	
NOL Shock Interaction	Aerophysics	26	1	40	6	1	-	-	-	$1\text{-}4\times10^{-3}$	Shock tube used to generate planar shockwave that intercepts model at test section
NASA-Ames Radiation Facility	Aerophysics	8	1	7-38	4	-	-	-	4	$1\text{-}10^{-3}$	Part of M = 7, shock-driven countercurrent wind tunnel.
VKF Counterflow Range	Aerophysics	2	0.5	13	3	-	-	-	-	-	Part of shock-driven countercurrent wind tunnel.
Boeing Aeroballistic Range[j]	Aerophysics Impact	10	0.75	13	6	1	1	-	1	-	
NOL Impact Range	Impact	10	2	13	-	-	3	-	-	$1\text{-}2\times10^{-3}$	1 rotating-mirror camera.
NRL Range No. 1[k]	Impact	15	1	-	2	-	9	-	-	-	
GM Ballistic Range A	Impact	5	0.3	6-8	3	-	-	-	-	-	$V_m \leqslant 10$ km/sec.
Douglas Range A[l]	Impact	1	0.3	13	3	-	-	-	-	$1\text{-}1.3\times10^{-8}$	
Douglas Range B	Impact	30	3	6-20	3	-	-	-	-	$10\text{-}4\times10^{-3}$	Telemetry.
GM-AC-DRL	Impact	3	1.5×2	57	2	-	-	-	-	-	Gun attitude adjustable.
NASA-Ames Impact Range	Impact	7	1	6	6	-	1	-	1	$1\text{-}10^{-3}$	$V_m \leqslant 11.3$ km/sec.

[a] US Naval Ordnance Laboratory; White Oak, Silver Spring; Maryland 20910, USA
[b] Canadian Armament Research and Development Establishment; P.O. Box 1427; Quebec 2, P.Q., Canada
[c] Royal Armament Research and Development Establishment; Fort Halstead, Sevenoaks, Kent; England
[d] Laboratoire de Recherches Balistiques et Aerodynamiques; Vernon (Eure); France
[e] ARO, Inc.; von Kármán Gas Dynamics Facility; Arnold Engineering Development Center; Arnold Air Force Station, Tennessee 37389, USA
[f] Ames Research Center; National Aeronautics and Space Administration; Moffett Field, California 94035, USA
[g] Massachusetts Institute of Technology; Lincoln Laboratory; Lexington, Massachusetts 02173, USA
[h] Institut Franco-Allemand de Recherches de Saint-Louis; 12, rue de l'Industrie; Saint-Louis (Haut-Rhin); France
[i] General Motors Corporation, AC Electronics; Defense Research Laboratories; 6767 Hollister Ave.; Goleta, California 93017, USA
[j] The Boeing Company; Aero-Space Division; P.O. Box 3707; Seattle, Washington 98124, USA
[k] US Naval Research Laboratory; Washington D.C. 20390, USA
[l] McDonnell-Douglas Aircraft Company; 3000 Ocean Park Blvd.; Santa Monica, California 90406, USA